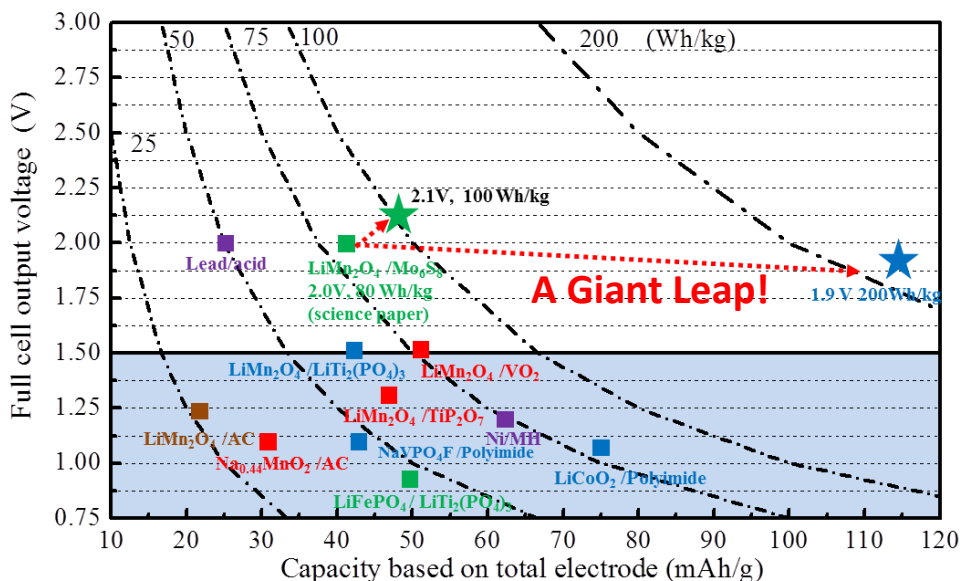


Multiple Electron Aqueous Li-ion Batteries

Technology Overview

- The electrochemical stability window of aqueous electrolyte has been expanded to **~3.1 volts** via the formation of SEI.
- A 1.9 V full cell using such electrolyte delivers a record-high **200 Wh/kg** (based on two electrode mass) for **200 cycles**.



Color code: **Red**: <100 cycles; **Blue**: 100 to 200 cycles
Green: >1000 cycles ★ : Our batteries

TEAM

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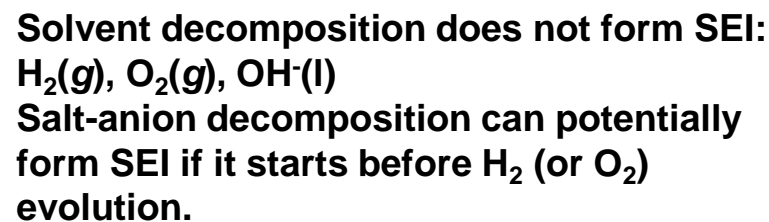
Current Status

- (1) **STATUS**: A safe 1.9V cell using 3.1V aqueous electrolyte can stably provide 200 Wh/kg (anode+cathode mass) for 200 cycles.
- (2) **NEXT TECHNICAL**: reducing cost of electrolytes
- (3) **NEXT COMMERCIAL**: Is collaborating with Saft American Inc. to build a 500 Wh demonstration unit.
- (4) **HELP NEEDED**: Cost modeling expert & new salts

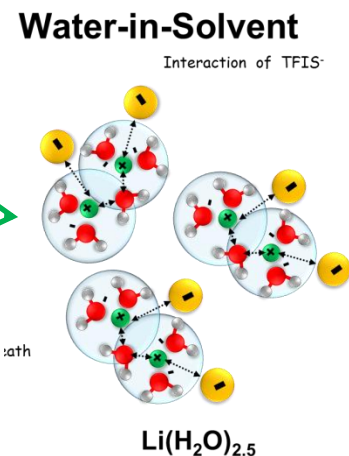
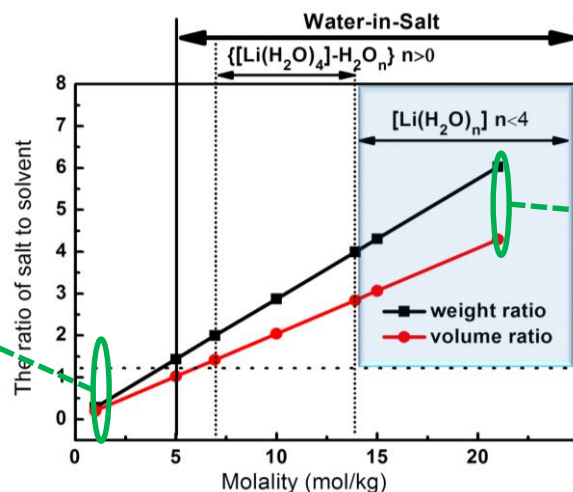
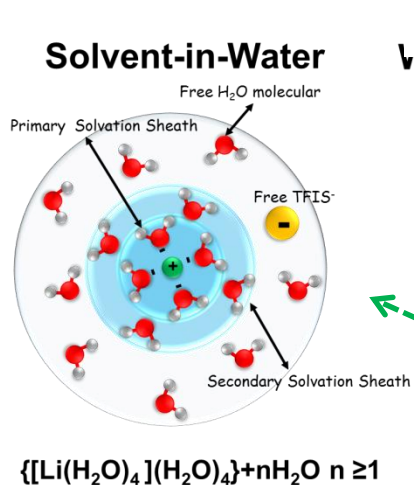
Project Statistics

Award Amount	\$1.1M
Award Timeline	Dec. 2013 – May. 2016
Next Stage Target	500 Wh prototype unit
Partners Sought	Saft, ARL, US TARDEC

2. Formation of solid electrolyte interphase (SEI) by high concentration of salt anion

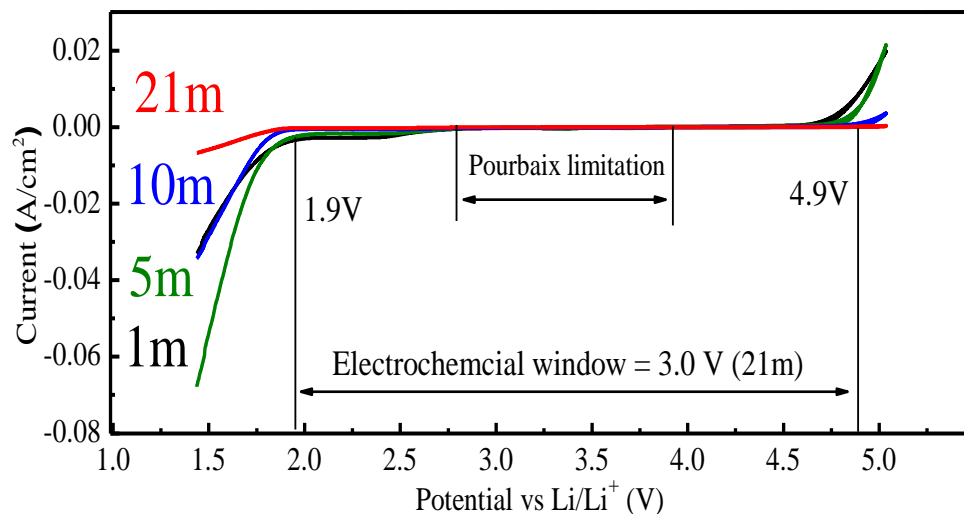


21 m Lithium bis(trifluoromethane sulfonyl)imide (LiTFSI) in water electrolyte

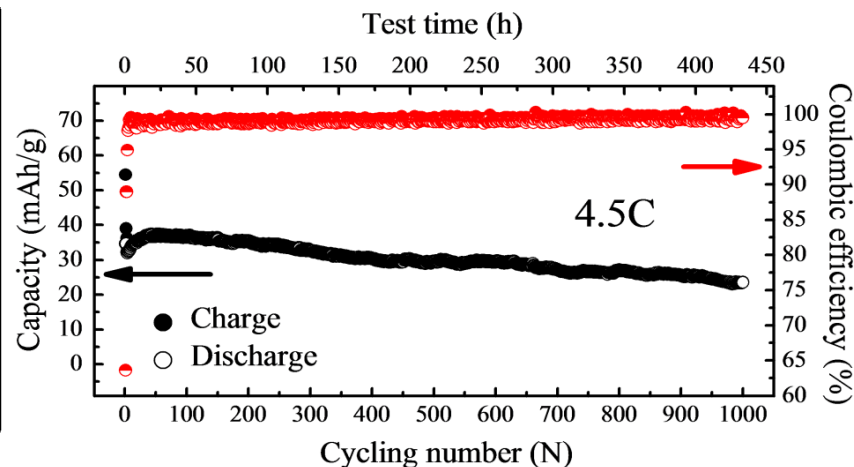


The change of weight and volume ratio of LiTFSI to H₂O with the molality of LiTFSI in H₂O

Photo picture of 21 m LiTFSI aqueous electrolyte



The electrochemical stability window



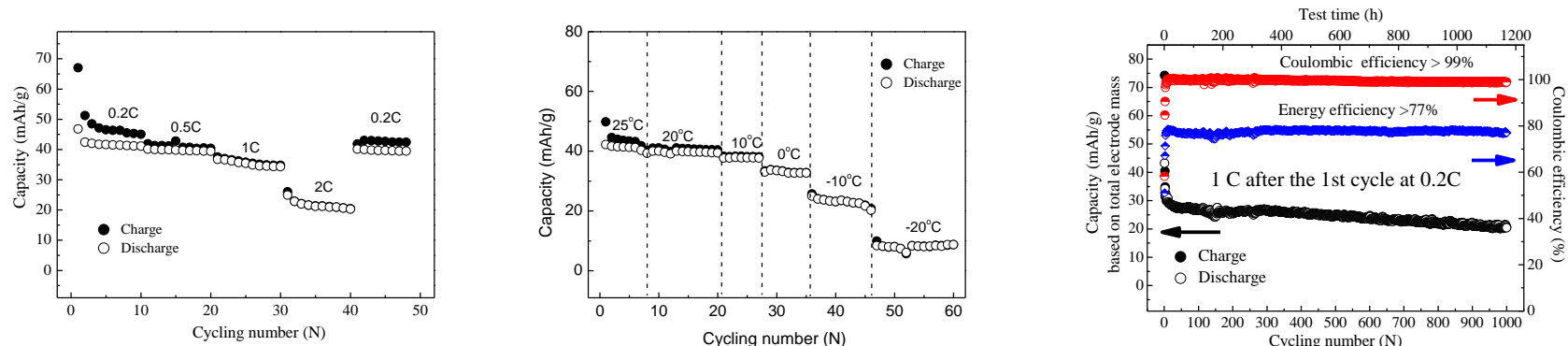
The progression of Raman vibration at ~744 cm⁻¹ with salt concentration;

Achievement reported in paper at *Science*

- Formed SEI for the 1st time in aqueous electrolytes
- Expanded electrochemical stability of aqueous electrolytes to **3.0 V**
- Assembled a **2.3 V aqueous LIB** that cycled **>1000** times at ~100% CE
- Energy density: **80~100 Wh/(Kg of total electrode mass)**;
- Stability at both low (0.15 C) and high (4.5 C)
- Absolutely safe

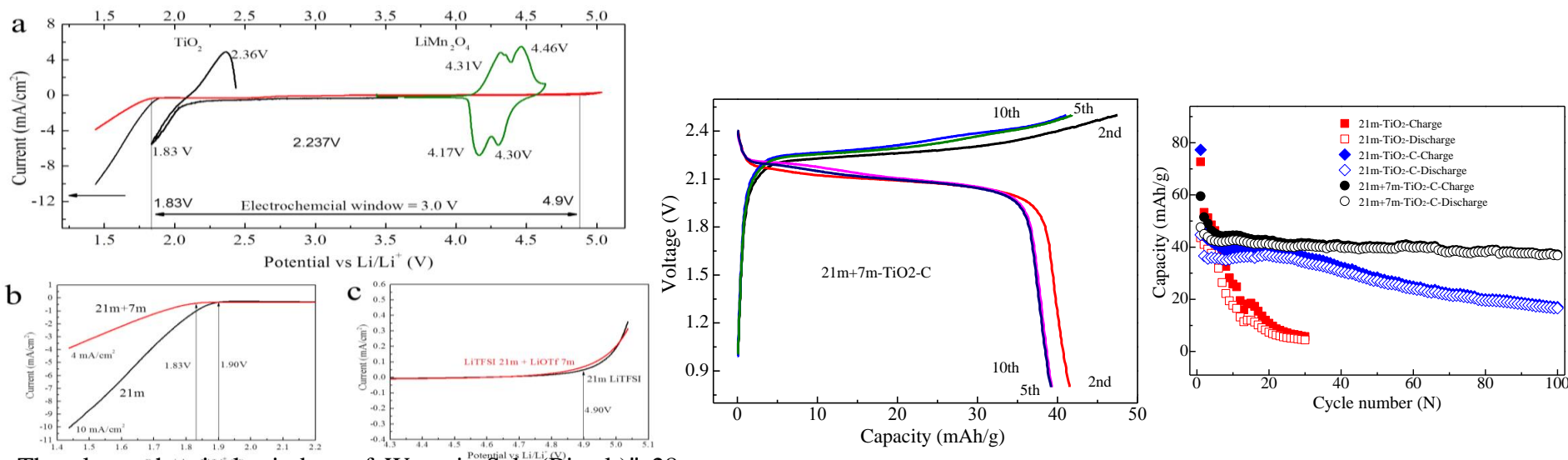
RESEARCH RESEARCH ARTICLES		Corrected 24 November 2015; see full text.	
BATTERIES		INSIGHTS PERSPECTIVES	
“Water-in-salt” electrolyte enables high-voltage aqueous lithium-ion chemistries		BATTERIES	
Liumin Suo, ¹ Oleg Borodin, ² Tao Gao, ¹ Marco Olguin, ² Janet Ho, ² Xiulin Fan, ¹ Chao Luo, ¹ Chunsheng Wang, ^{1*} Kang Xu ^{2*}		Opening the window for aqueous electrolytes	
Lithium-ion batteries raise safety, environmental, and cost concerns, which mostly arise from their nonaqueous electrolytes. The use of aqueous alternatives is limited by their narrow electrochemical stability window (1.23 volts), which sets an intrinsic limit on the practical voltage and energy output. We report a highly concentrated aqueous electrolyte whose window was expanded to ~3.0 volts with the formation of an electrode-electrolyte interphase. A full lithium-ion battery of 2.3 volts using such an aqueous electrolyte was demonstrated to cycle up to 1000 times, with nearly 100% coulombic efficiency at both low (0.15 C) and high (4.5 C) discharge and charge rates.		Lithium batteries can operate with a safer “water-in-salt” electrolyte	
By Leland Smith and Bruce Dunn		By Leland Smith and Bruce Dunn	
Lithium-ion (Li-ion) batteries power much of our digital and mobile lifestyle (1, 2). However, their adoption in more strategically important applications such as vehicle electrification and grid storage has been slower, mainly because of concerns raised over their safety, cost, and environmental impact (3).		By facilitating ion motion between electrodes, electrolytes help to harness the chemical energy in a battery to produce a current and supply usable electric power. Among liquid electrolytes, there are traditional solutions of salt	
the overall electrochemical stability window of aqueous electrolytes remains constant, anodic stability against oxygen evolution suffers a corresponding compromise, as illustrated by a Pourbaix diagram (9). A maximum voltage of 1.5 V was achieved in aqueous Li-ion batteries, where the residual currents for H ₂ or O ₂ evolution still		sis can occur. For other electrolyte-electrode combinations, electrolyte breakdown can result in the formation of insoluble solid materials at the electrode surface (4). These decomposition products can widen the effective voltage stability range of the electrolyte above the thermodynamic value. The electrolyte solvent, salt, and elec-	
in water. This leads to an anion-coordination solvation sheath, which results in the formation of a dense interphase on the anode surface arising from anion reduction. Combining this with a substantially reduced electrochemical stability window of water at such a high concentration of concentrated water-in-salt electrolyte, we achieved an expanded electrochemical stability window of ~3.0 V. A full aqueous Li-ion battery with a model electrochemical couple of Mo ₆ S ₈ demonstrated an open-circuit voltage (OCV) of 2.3 V and was cycled 1000 times with nearly 100% coulombic efficiency for up to 1000 cycles at both low (0.15 C) and high (4.5 C) discharge and charge rates.		ceeding what is typically obtained from aqueous electrolytes. The high stability is attributed to the electrochemical reduction of bis(trifluoromethane sulfonyl)imide at the anode surface, which forms an SEI layer consisting primarily of LiF, and is accompanied by a shift in the oxygen evolution reaction to higher voltages (1). The electrolyte solvent, salt, and elec-	
Water-in-salt electrolytes		There are traditional solutions of salt	
LiTFSI was chosen as the salt because of its high solubility in water (>20 m at 25°C) and stability against hydrolysis (25). When the concentration is above 5 m, the “water-in-salt” definition applies, as the salt outnumbers water in this binary system by both weight and volume (fig. S1). In these solutions, the average number of water molecules available to solvate each ion is far below the “solvation numbers” that are well established in conventional electrolytes (~10 m). Instead, interionic attractions become more pronounced relative to solvent-ion interactions, incurring unusual physicochemical properties (16–20). More important, the inter-		There are traditional solutions of salt	

Long cycle life Aqueous $\text{LiFePO}_4/\text{Water-in-Salt}/\text{Mo}_6\text{S}_8$ Li-ion Battery for Electric Energy Storage



L. Suo, F. Han, X. Fan, H. Liu, C. Wang and K. Xu, *Journal of Materials Chemistry A*, DOI:10.1039/C6TA00451B, (2016)

High Voltage Li-ion battery using Water-in-Bisalt electrolyte



The electrochemical window of Water-in-Salt (Bi-salt) 28 mLiTFSI-LiOTf electrolyte and the 1st CV traces of active anode (C/TiO_2) and cathode (LiMn_2O_4) materials measured at scanning rate of 0.1 mV/s in the same electrolyte,

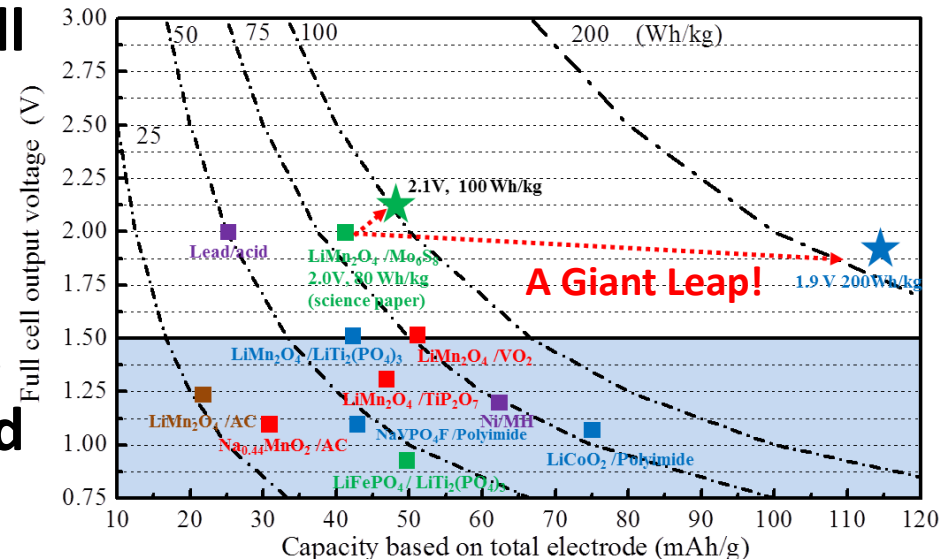
Achievement Since the paper in *Science*

- Further expanded the stability window to **3.1 V**
- Employed **more energetic** electrochemical couple
 - Cathode: LCO, NMC, and LMNO
 - Anode: high capacity anode

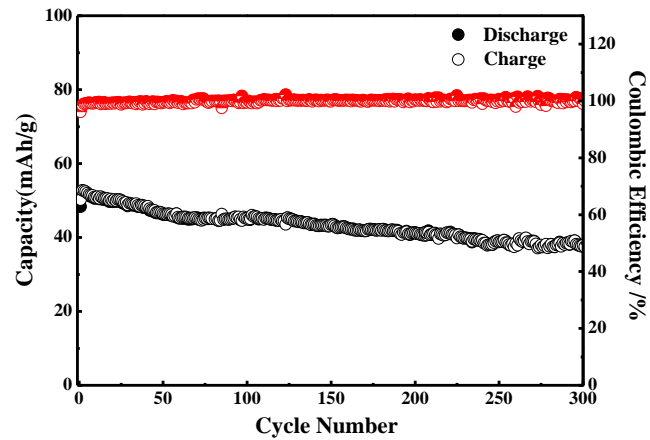
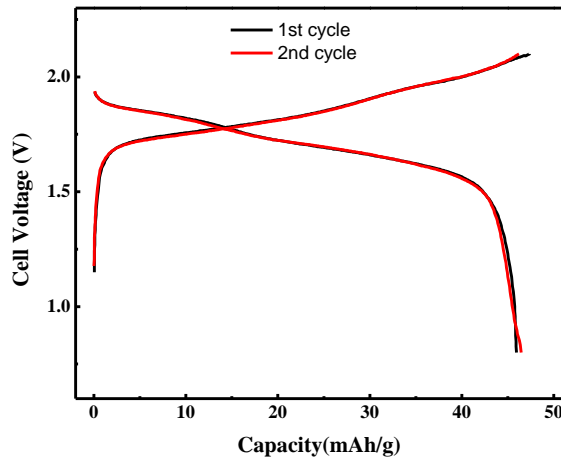
Color code:
Red: <100 cycles
Blue: 100 to 200 cycles
Green: >1000 cycles
★: Our batteries

A Giant Leap: A few aqueous LIB full cells made, energy density up to **200 Wh/(Kg of total electrode mass)**

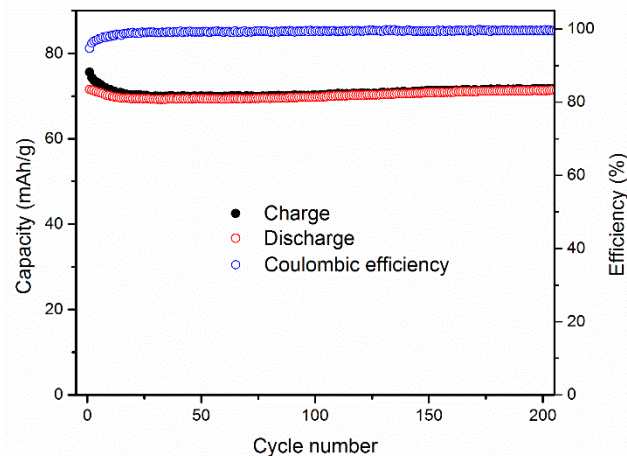
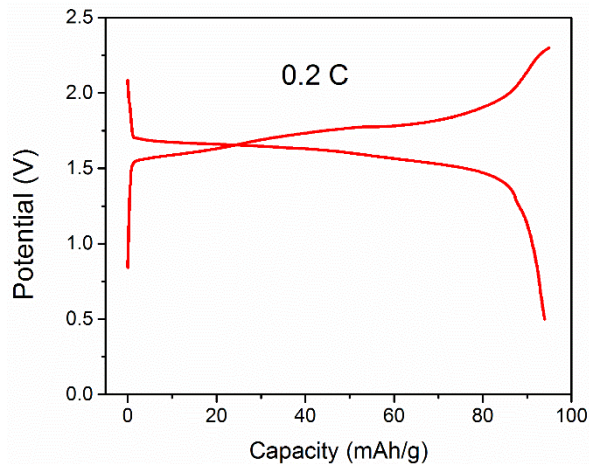
- Considering that *dry room, BMS, packaging* etc could be simplified or eliminated at pack/module level, energy density becomes competitive or even superior to non-aqueous LIB



High Energy Aqueous Li-ion Batteries based on various Chemistries



The cycling of the new 1.9 V aqueous LIB with Mo₃S₄ and Cathode LCO



The cycling of the new 1.7 V aqueous LIB with Anode Y and Cathode LMO